# Chapter XXIX
# Autonomous Systems with Emergent Behavior

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## ABSTRACT

*This chapter presents the notion of autonomous engineered systems working without central control through self-organization and emergent behavior. It argues that future large-scale applications from domains as diverse as networking systems, manufacturing control, or e-government services will benefit from being based on such systems. The goal of this chapter is to highlight engineering issues related to such systems, and to discuss some potential applications.*

## INTRODUCTION

Devices from personal computers, to handhelds, to printers, to embedded devices are very widely available. Further, today's wireless network infrastructures make it possible for devices to spontaneously interact. In addition, large-scale communication, information, and computation infrastructures such as networks or grids are increasingly being built using numerous heterogeneous and distributed elements, which practically cannot be placed under direct centralized control. These elements exhibit certain degrees of autonomy and of self-organization, such as taking individual decisions and initiatives, interacting which each other locally, and giving rise to an emergent global behavior.

This chapter introduces first the notion of autonomous systems; second it reviews the notions of decentralized control, self-organization, and emergent behavior, and discusses how they relate to each other. Third, this chapter discusses different issues pertaining to the design and development of autonomous systems with emergent behavior. Fourth, it reviews techniques currently being established for building those systems. Finally, it provides several examples of applications.

## AUTONOMOUS SYSTEMS

We distinguish different classes of autonomous systems. First, autonomous systems as *distributed embedded devices* consist of physical devices having some onboard intelligence, and standalone and communication capabilities. Such devices comprise intelligent mobile robots, but also intelligent wearable computing, surveillance, or production devices. Second, from a software point of view, *autonomous agents and multi-agent systems* are a notion first established by the distributed artificial intelligence community. Such systems do not have to cope with the same problems faced with devices situated in a physical environment (e.g., low battery). However, agents provide a metaphor for software design which incorporates most of the elements present in embedded devices such as autonomous decision-taking processes, communication with other agents, and social interactions for collaboration, negotiation, transactions or competition purposes (Wooldridge, 2003). Third, more recently an initial focus has been given from the research community on autonomous software entities interacting with each other in a decentralized self-organized way in order to realize a dedicated high-level functionality (interactions for collaboration purposes), or giving rise to an emergent global behavior as a side effect of their local interactions (interactions for competition purposes). This category of applications or entities is referred to as *self-organizing systems* or *systems with emergent behavior* (Di Marzo Serugendo et al., 2004). In some sense, this last category combines the first two views where autonomous software populates autonomous devices. Fundamental points of these different views of autonomous systems are: the social interactions arising among the different elements, and the need for adaptation to unforeseen (at design time) situations encountered in dynamic environments.

There is currently a growing interest in autonomous applications able to self-manage, not only from academic research but also from the industry. *Ambient intelligence* envisions seamless delivery of services and applications, based on ubiquitous computing and communication. Invisible intelligent technology will be made available in clothes, walls, or cars; and people can freely use it for virtual shopping, social learning, micro-payment using e-purses, electronic visas, or traffic guidance system (Ducatel et al., 2001). Ambient intelligence requires low-cost and low-power designs for computation running in embedded devices or chips, as well as self-testing and self-organizing software components for robustness and dependability. Based on the human nervous system metaphor, IBM's *Autonomic Computing* initiative considers systems that manage themselves transparently with respect to the applications. Such systems will be able to self-configure, self-optimize, self-repair, and protect themselves against malicious attacks (Kephart & Chess, 2003). Recent interest by Microsoft, as part of the *Dynamic Systems Initiative,* indicates as well the importance of self-organization for managing distributed resources.

### Autonomous Computation Entities vs. Autonomous Systems

As follows from the discussion above, autonomous systems are composed of one or, more generally, of several autonomous computation entities interacting together. These autonomous computation entities are either embedded into physical, possibly mobile, devices (e.g., in ambient intelligence applications) or part of a given environment that supports their execution and interactions (e.g., multi-agent systems).